TOWARD DIRECT ACCESS INTELLIGENCE SYSTEMS

Sponsored by

THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
under Grant
AF-OSR 70-~~1965~~
1865

INTERIM TECHNICAL REPORT

for the Period
31 May 1970 - 31 October 1970

Prepared by
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Submitted
15 December 1970

BIOLOGICAL COMPUTER LABORATORY
UNIVERSITY OF ILLINOIS
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TOWARD DIRECT ACCESS INTELLIGENCE SYSTEMS

I. INTRODUCTION

The Department of Electrical Engineering of the University of Illinois conducted through its Biological Computer Laboratory an interdisciplinary basic research program who principal aim was establishing the conceptual, theoretical and experimental foundations for the development of intelligence systems which permit direct access to their data base via natural language and establish this data base through man-machine interactions in natural language and/or through interactions with their remote or inaccessible environments.

The program was a continuation of activities sponsored under the auspices of the current AFOSR Grant 70-1865, Application of Cognitive Systems Theory to Man-Machine Systems, and its predecessors. It was proposed that this program extend over a period of two (2) years in order to provide for the completion of long range research projects and of Doctoral Theses of participating graduate students from Departments of Electrical Engineering, Mathematics, Biophysics and Physiology.

II. DESCRIPTION OF STUDY

A. Abstract

In contrast to conventional so called "Information Storage and Retrieval Systems" which de facto store indexed documents (the data base) which upon retrieval may or may not contain the information needed by the querier who is to address such systems through highly restricted and artificial indexing languages, this project aims at the development of a data base which organizes the intelligence stored in a machine such that the desired knowledge is directly accessible to the user through a man-machine dialogue in the user's natural language.

The feasibility of this approach to direct access intelligence systems (DAIS) is strongly indicated by recent results obtained by various investigators elsewhere and by members of this laboratory under the auspices of the current and previous AF-OSR grants in the development of relational data structures and interacting machine programs which permit computing in the semantic domain, and in logic, theory and experimental studies of cognitive processes in living organisms.

Consequently, it was proposed to continue and to complete the research and development of the conceptual, theoretical and technological foundations for the development of machine intelligence systems with direct access to a user's desired knowledge via a man-machine dialogue in the user's natural language.

B. Detailed Description

The following Sections give a brief report on the activity on current Grant AFOSR 70-1865 during the period from 31 May 1970 to 31 October 1970. Section (1) gives an account of the personnel which contributed to this research project during this period. Section (2) summarizes the accomplishments during the same period. The publications issued under this sponsorship within the dates indicated above are listed in Section (3).

(1) Personnel

The following list contains the names, the ranks, and the departmental affiliations of all members of the Biological Computer Laboratory who are, or were, part-time or fulltime engaged in the research program sponsored under the auspices of the current AFOSR Grant 70-1865 during the five month period from 31 May 1970 to 31 October 1970.

Ashby, W. R.	Professor	EE and Biophysics
Brieske, G.[1]		
Duran, P.	Res. Assistant	Mathematics
Ficken, J.	Hourly Student	
Gruberg, E.[1]		
Gunther, G.	Professor	EE
Howe, R.	Hourly Student	
Inselberg, A.[1]		
Kokjer, K.	Res. Assistant	Biophysics
Madden, R.	Res. Assistant	EE
Marzullo, E.	Res. Assistant	Physics
Maturana, H. R.	Vist. Res. Professor	Physiology
Peterson, A.	Hourly Student	
Peterson, L. J.	Res. Assistant	Computer Science
Pukszta, F.	Hourly Student	
Saxema, K.	Res. Assistant	EE
Taylor, S.	Res. Assistant	EE
Von Foerster, H.	Professor & Director	EE and Biophysics
Weston, P.	Res. Associate	EE
Wilkins, M.[1]		
Wolf, D.	Hourly Student	

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1 No longer associated; paper published during report period.

(2) Progress Summary

In comparison to today's highly developed technologies for data acquisition (photo-reconnaissance, intelligence, ledgers, scientific results, population dynamics, economics, legal decisions, opinion polls, etc., etc.) the development of technologies for the utilization of these data is still in an infant state. This is to nobody's surprise whoever encountered the formidable difficulties when contemplating ways of solving the latter problem as compared to the relative ease with which the former problem can be solved. While when recording data any device that records (from pencil and paper to holograms) will do, the question as to how these records can be utilized involves not only an understanding of the physical properties of the records but also an understanding of the processes by which the user of these records may utilize their contents. In other words, linked to the question of utility are the enigmatic properties of the user and his cognitive apparatus which "lifts", so to say, from the data the information he desires.

Until not too long ago this conceptual bottleneck was not visible at all, for in many cases knowledge about facts could be obtained by direct observation ("seeing is believing") or by descriptions which could be easily classified into "natural" categories and thus could be retrieved by calling

upon the appropriate "key words". Today, however, in most cases things we wish or ought to know can neither be observed directly--they may be part of a hostile environment--nor can their description be classified into meaningful categories--their numbers having grown too large--and hence they can't be found.

Today's multi-billion dollar effort which attempts to overcome these difficulties by fighting complexity with speed has followed essentially the conventional line of reproduction and classification of the documents (records) which constitute the data base. A document (which hopefully contains the desired information) is then retrieved through especially designed keywords, abstracts, indexes and index languages, paying attention to the user only insofar as to consider the limits of his adaptation to the demands of the technology to be employed. As a consequence of this strategy present intelligence systems designed for direct observations or for retrieval of descriptions suffer from a common ailment: the chances for obtaining relevant information decline with the size of their data base. In other words, adding new data to such systems diminishes their utility.

This is in ominous contrast to the way in which man and, as a matter of fact, all living organisms acquire their knowledge: the more they have experienced the wiser they get. Consequently, an intelligence system which enhances by the growth of its data base the utility for its user must

exhibit functional properties which are homomorphic to those of the user: the "information impedance" (1) of user and system must be matched at all times. One consequence of this postulate can readily be seen: the interaction between man and machine must proceed by means of a dialogue in the user's natural language.

From this it appears to be clear that this approach to machine intelligence represents a radical departure from conventional strategies, hence, the categories of problems to be solved are in many substantial points quite apart from those commonly being considered. On the other hand, it appears to be also clear that this approach will--when solved--introduce a profound change in the entire field of information processing in as much as the dreaded "information explosion" works now to the user's advantage who has direct access to descriptions of facts which he desires to know.

While there may arise no major argument about the desirability of such direct access knowledge acquisition systems, considerable doubt may be raised as to their technological and economical feasibility. Since the economy of any system is only understood when its technology and operations are known and, moreover, since the concept of economic utility of information is--except in game theory--still standing on shaky grounds (what is the value, in dollars and cents, of Paul Revere's message "They approach by sea."?) it is proposed to make this question part of the studies to be conducted in

the forthcoming period. The technological feasibility, however, can be defended now, drawing on the knowledge gained in part by various other research groups, and in part by the current and previous activity under this grant's sponsorship. Here, two major accomplishments put us in an optimistic mood. One is a better understanding of the relationship between perception, language and behavior (2)(3), the other is the solution of the problem of a machine representation of a relational data structure (4). Both of these accomplishments have a crucial effect on the realizability of Direct Access Intelligence Systems (DAIS), for the road is now open to incorporate into machines the semantic relational structure into which experience is projected either through observation or through dialogue. Of course, this project is not the only one which addresses itself to this problem.

Throughout the roughly ten year history of attempts to simulate in machines the understanding of natural language, the one theme common to all the undertakings has been the use of a semantic model formulated in terms of relations, or a relational data structure (5)(6)(7)(8)(9) to represent meanings. Upon this point all have agreed who are concerned with meaning and language. Still, important variations in emphasis have characterized the different studies, and, at times, important differences in strategy. The range of emphasis runs from a near minimum concern with language as such, in which case the subject merges with logic and the

simulations of deductive processes (6)(10) to the opposite extreme represented by the linguists concerned with the "deep-deep structure" who have engaged themselves with important questions in the analysis of meaning from the standpoint of transformational grammar (11)(12)(13), but have not become further involved in relational formulations.

The approach presented herein, however, demands a serious attempt to deal with the connections between the relational model and language, and thus with the subject matters of both of the extreme approaches above. There are, at the highest level of generality, two important and interrelated aspects to the problem:

(a) What form a relational semantic model must take in order that it may adequately represent meanings, not only of individual words but of phrases, sentences and larger units?

(b) Given the logical form of an adequate representation what are its actual contents such that a particular language vocabulary or text are accurately represented?

Regarding the necessary logical form, all of the work represented by the first group of references above has embodied simplifications in form which have been acknowledged explicitly or are readily demonstrable. However, an adequate model requires the representational power of higher order logical calculi which are now beginning to emerge in the literature(14).

Passing to the second major issue, the identification of the elements of meaning in a particular language and

vocabulary, there is relatively less to build upon, in comparison to the magnitude of the final objective. It is useful to deal with the issue in terms of three major avenues of approach, each of which is represented in prior work, and which taken together, fairly represent the tools now available to us in our anticipated further pursuit of the subject. These are:

(a) Discovery of the primitive elements in referential meanings.

(b) Elucidation of the relations which are expressed purely by grammatical structure.

(c) Systematically examining the semantically acceptable and semantically unacceptable contexts for given words, particularly those ordinarily considered to be non-referential, in order to deduce their corresponding logical properties.

In pursuing this approach we have available, in addition to Olney's (15) results, results from our own studies in which a systematic method of dictionary search was used to reveal potential semantic primitives. These must then be given an interpretation at the logical structure level and tested for consistency by examining the interpretation of the linguistic constructions in which they may appear. The process, though laborious, interacts beneficially with the other two avenues of approach to the mappings of syntactic structure.

Two sources are representative of the prior work in the analysis of the significance of grammatical relations, our second major method of approaching semantic structure (16)(17). Fillmore (16) has worked from the viewpoint of transformational grammar and so requires reinterpretation for our purposes, but he has uncovered the existence of a variety of relationships which are highly germaine to a logical formulation, and which are represented in a variety of ways by the "non-representational" or grammatical elements of sentences such as auxiliary verbs and the "small" prepositions, and more generally, purely grammatical relationships involving the order of sentence elements.

The type of work discussed above is closely allied to the third type listed earlier in which words, including the so-called "grammatical" or "function" words, are examined in context for clues to their logical properties. Both methods, in contrast to the first, must begin with words in actual use and not in isolation, as in a dictionary. This results in considerable interplay and overlap in actual execution.

In summary, we may conclude that with both approaches, we are pursuing the intriguing hypothesis that what is in fact represented at this "non-representational" level is the structure of the generally accepted cognitive framework which in a particular society underlies ordinary discourse and is simply taken for granted. This is meant to include such

fundamental concepts as those of time and space, as reflected in everyday usage rather than in the more precise formulations of physical theories; or those of cause and effect, ownership, other person-to-person or person-to-object relationships through the cognitive counterparts, if any, of grammatical number or gender. Results so far suggest the correctness of our hypothesis, and that the relationships which come out as elements of the cognitive framework, reappear as primitive concepts in the structure of the referential vocabulary, lending a higher level of unity to the system of semantic and cognitive relationships we are trying to uncover.

At present, however, we are going to exploit to the fullest extent the achievements of our previous work, particularly the potentials of the relational data structure (4) for the mechanization of the deductive process (18) and for computing in the semantic domain (19).

It is easy to see that the realization of logical deduction by machine occupies an important sector in the development of direct access intelligence systems, for it is through the transforming of information without recourse to other resources, that is *deduction*, that an intelligence system may be given the power to uncover the relationships which are contained but not explicit in a body of data, and thereby achieve a new and higher level of usefulness. Deductive transformations are required in three important tasks

of an advanced intelligence system:

(a) Answering of questions which cannot be answered by extracting explicit material, because of either a difference in terminology or the fact that the answer is still only implicit in the stored data,

(b) Detecting paraphrase when differing formulations of the same relationship appear within the data, thereby avoiding redundancy and/or confusion in both storage form and subsequent answers,

(c) Matching the terminology in an answer to the competence and interest of the user, when these differ from the characteristics of the data source(s).

At present,the HIRWON algorithm (18) has achieved an extension of the capacity previously available for machine deduction based directly upon semantic relational models (5) (6)(7), as distinguished from procedures based directly upon formulations in a mathematical notation, e.g., first- or a higher-order logical calculus (8)(10)(20).

HIRWON's extension of deductive power has been made possible basically by expanding the representational power of the semantic model to include items which are specified only indirectly through some of their relationships with other items in the structure. Nonetheless, in HIRWON, not all possible avenues of approach to semantically-based deduction have been used, and in particular, the algorithm presently relies heavily upon the restrictive properties of

relations, which have also been profitably exploited, though in different ways, in other question-answering systems (21) (22). An important direction of extension has been suggested by some of the previous work with problem-solving programs in various mathematical domains, e.g., algebra or calculus (23)(24)(25)(26). With the requirements of a technical intelligence system in view, an examination of the deductive tasks (b) and (c), which involve translation from one to another formulation, shows that the use of formal mathematical machinery is very likely to be required in going from one to another form of expression of a given relationship. For one purpose it might, for instance, be adequate to state in verbal form a relationship such as

(A) "The rate of increase in the number of scientific periodicals at an arbitrary instant of time is proportional to the number of scientific periodicals at that time."

While for another purpose it could be more illuminating to state the essentially equivalent form:

(B) "The number of scientific periodicals increases by a constant ratio over each successive decade."

The forms (A) and (B) derive their equivalence through well-known procedures for transforming mathematical formulae, in this case by elementary calculus, and are not related directly through any semantic properties. Because paraphrases such as (A) and (B) are important, and because there does

exist a body of work dealing with obtaining mathematical solutions in symbolic form by machine, we will attempt to extend our semantically-based approach to include formal manipulations of this general sort. The problems involved will be somewhat different than in the previous work, however. That is, on the purely semantic level, the relevance or lack of relevance of a mathematical formulation must be detected. This problem did not exist in previous specialized systems. Secondly, there is an important shift in viewpoint because in most mathematical contexts the form of the problem and the form of its solution can be assumed, while here the usual distinction between problem and solution becomes irrelevant, insofar as either (A) or (B) could, for instance, be the initial or final form desired. What is the problem and what the solution depend upon matters outside of the data themselves and are determined by the characteristics of the users of the system.

In the light of the general objectives of this work this undertaking is intended as a selective attack upon the larger field of essentially extra-semantic inference processes whose interplay with the linguistic conceptual domain is so fundamental to the cognitive behavior which we are trying to reproduce.

A bridge between behavior in general and verbal behavior in particular is provided by an important theorem by Maturana (3)(27) which in essence postulates the primacy of connotation

over denotation; and connotation, in turn, as being derived from "orienting" behavior. This theorem which provides a central view of interpretation for many and disparate observation in neurophysiology and psychology (28)(29) is, in turn, supported by epistemological studies in the logical structure of concepts as "self-explanation" (30), "self-reference" (31), "autonomy" (2), etc., which refer to the two-sidedness of the phenomenon of cognition which, on the one hand, has to account for subjective experience (subjectivity), and on the other hand for the communicability of subjective experience (objectivity = shared subjectivity).

In the context of this research program the most significant finding of these studies is the interdependence of an organism's perceptive system with its motor system or, to put it differently, the effect of an organism's action on the organization of its sensorium (32) and, vice versa, the effect of an organism's sensations on the organization of its motorium (33).

Since these interactions control, and are controlled by, the semantic model of the organism's environment, it is these observations which establish the link between purely intelligence systems and remotely operating "automata" which selectively collect, process, transform and transmit meaningful information autonomously, quickly and reliably to human observers who interact with this system during its mission through dialogue in natural language. Considering the extraordinary

small channel capacity (band width) which is required for transmitting messages in alpha-numeric codes (or, as a matter of fact, in natural speech) compared to video signals or other poorly encoded messages, the advantage of such devices is obvious and need not be further stressed.

In summary it appears that today's state of the art (and in particular the knowledge gained in this laboratory) in semantic modeling, in programming of relational data structures and in the epistemology and theory of cognitive processes provide a sufficient basis for contemplating seriously the preparatory steps for the construction of machine intelligence systems for the acquisition of knowledge about facts or description of facts through man-machine dialogue in the user's natural language.

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$$Z_I = H_{max}/H \cdot v \quad [\text{seconds}].$$

This number is high in man ($\sim 10^7 \div 10^{10}$ sec), but low

for high speed digital computer systems ($\sim 10^7 \rightarrow 10^{-2}$ sec.). However the information impedance mismatch ($\sim 10^{12}$) in the man-machine interface has in the last decades been reduced (to $\sim 10^6$) by various "anthropomorphizing" devices (programs, program languages, compilers, large storage systems, time sharing, etc.). This mismatch, however, is still beyond tolerance for a direct access intelligence system.

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University of Illinois
Urbana, Illinois

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UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) University of Illinois Biological Computer Laboratory Urbana, Illinois 61801	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

TOWARD DIRECT ACCESS INTELLIGENCE SYSTEMS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Scientific Interim

5. AUTHOR(S) (First name, middle initial, last name)

Heinz Von Foerster

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
15 December 1970	23	54

8a. CONTRACT OR GRANT NO AFOSR-70-1865	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. 9768-02	
c. 61102F	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d. 681305	AFOSR 70-2991TR

10. DISTRIBUTION STATEMENT

1. This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
TECH, OTHER	AF Office of Scientific Research (NE) 1400 Wilson Boulevard Arlington, Virginia 22209

13. ABSTRACT

In contrast to conventional so called "Information Storage and Retrieval Systems" which de facto store indexed documents (the data base) which upon retrieval may or may not contain the information needed by the querier who is to address such systems through highly restricted and artificial indexing languages, this project aims at the development of a data base which organizes the intelligence stored in a machine such that the desired knowledge is directly accessible to the user through a man-machine dialogue in the user's natural language. The feasibility of this approach to direct access intelligence systems (DAIS) is strongly indicated by recent results obtained by various investigators elsewhere and by members of this laboratory under the auspices of the current and previous AFOSR grants in the development of relational data structures and interacting machine programs which permit computing in the semantic domain, and in logic, theory and experimental studies of cognitive processes in living organisms.

Consequently, it was proposed to continue and to complete the research and development of the conceptual, theoretical and technological foundations for the development of machine intelligence systems with direct access to a user's desired knowledge via a man-machine dialogue in the user's natural language.

DD FORM 1 NOV 65 1473

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Security Classification